

CHARACTERIZATION OF CELLULOSE TRI ACETATE (CTA) FORWARD OSMOSIS MEMBRANE FOR NOM REMOVAL

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ABSTRACT

Nowadays, to cater for the increasing population in Malaysia, drinking water is taken primarily from surface water sources like rivers, lakes, and reservoirs. These surface water sources need to be treated correctly at low cost and energy before consuming by the citizens. Among all the methods used, forward osmosis (FO) fits the best. In lieu of hydraulic pressure, forward osmosis is separation process which utilizes a highly concentrated draw solution to induce the driving force for water to permeate across the membrane. This research focuses on the characterization of Cellulose Tri Acetate (CTA) Membrane performance in forward osmosis process to treat synthesized river water containing natural organic matter (NOM) which is humic acid with concentration of 15mg/L by using sodium chloride (NaCl) solution as the draw solution. This research was conducted based on the concentration of NaCl draw solution which is a parameter that will impact the water flux and performance of forward osmosis which are humic acid rejection and reverse salt diffusion. In addition, the impact of feed solution pH on the process was investigated. The humic acid rejection was measured by UV-Vis Spectrometer while reverse salt diffusion was measured by conductivity meter. Based on the results obtained, increase in the concentration of NaOH in feed solution increases the pH which ultimately affect the water flux, humic acid rejection and reverse salt diffusion. Besides, it is shown that increase in both draw solution concentration and feed solution pH increase the water flux. The water flux obtained by using related formula showed the highest figure by 2.5M NaCl draw solution with the reading of $1.580 \times 10^{-6} \text{ m}^3/\text{m}^2.\text{min}$ for feed solution pH of 9.73 and $2.054 \times 10^{-5} \text{ m}^3/\text{m}^2.\text{min}$ for feed solution pH of 11.65. Furthermore, the increase in draw solution concentration causes a decrease in humic acid rejection for both feed solutions with pH of 11.65 showed a higher solute rejection of more than 97%. It is also shown from the result that the increase in draw solution concentration and water flux causes an increase in reverse salt diffusion for both feed solutions with pH of 9.73 showed a higher reverse salt diffusion. Based on the discussions, it is found that the optimum condition for treating river water by using CTA membrane can be achieved at high concentration of draw solution with high pH of feed solution. By completing this research, the effectiveness of using CTA membrane to treat river water in Malaysia by forward osmosis process can be investigated and the optimum condition of the process will be determined in order to overcome the problem of water depletion in Malaysia.

ABSTRAK

Pada masa kini, untuk menampung populasi yang semakin meningkat di Malaysia, air minuman diambil terutamanya daripada sumber air permukaan seperti sungai, tasik, dan takungan. Air permukaan ini perlu dirawat pada kos dan tenaga yang rendah sebelum dipakai. Antara kaedah-kaedah yang digunakan, osmosis hadapan merupakan kaedah yang paling sesuai. Sebagai gantian tekanan hidraulik, osmosis hadapan menggunakan larutan penarik pekat untuk mendorong daya penggerak untuk pemisahan melalui membran. Kajian ini memberi tumpuan kepada pencirian prestasi Membran Selulosa Tri Acetate (CTA) dalam proses osmosis hadapan untuk merawat air sungai yang disintesis mengandungi bahan organik semulajadi (NOM) iaitu asid humik dengan kepekatan 15mg/L dengan menggunakan larutan natrium klorida (NaCl) sebagai larutan penarik. Kajian ini dijalankan berdasarkan kepekatan larutan penarik NaCl yang merupakan parameter yang memberi kesan kepada fluks air dan prestasi osmosis hadapan iaitu penolakan asid humik dan penyebaran garam terbalik. Selain itu, kesan pH larutan suapan kepada proses juga dikaji. Penolakan asid humik telah diukur dengan UV-Vis Spektrometer manakala penyebaran garam terbalik diukur dengan meter konduktiviti. Berdasarkan keputusan, peningkatan kepekatan NaOH dalam larutan suapan meningkatkan pH yang memberi kesan kepada fluks air, penolakan asid humik dan penyebaran garam terbalik. Selain itu, ia menunjukkan bahawa peningkatan dalam kepekatan larutan penarik dan pH larutan suapan meningkatkan fluks air. Fluks air yang diperolehi dengan menggunakan formula berkenaan menunjukkan angka tertinggi oleh 2.5M larutan penarik NaCl dengan bacaan $1.580 \times 10^{-6} \text{ m}^3/\text{m}^2.\text{min}$ untuk pH larutan suapan sebanyak 9.73 dan $2.054 \times 10^{-5} \text{ m}^3/\text{m}^2.\text{min}$ untuk pH larutan suapan sebanyak 11.65. Peningkatan kepekatan larutan penarik menyebabkan penurunan penolakan asid humik untuk kedua-dua larutan suapan dengan pH 11.65 menunjukkan penolakan bahan larut yang lebih tinggi melebihi 97%. Ia juga ditunjukkan bahawa peningkatan dalam kepekatan larutan penarik dan fluks air menyebabkan peningkatan dalam penyebaran garam terbalik untuk kedua-dua larutan suapan dengan pH 9.73 menunjukkan penyebaran garam terbalik yang lebih tinggi. Berdasarkan perbincangan, didapati bahawa keadaan optimum untuk merawat air sungai dengan menggunakan membran CTA boleh dicapai pada kepekatan larutan penarik dan pH larutan suapan yang tinggi. Dengan kajian ini, keberkesanan penggunaan membran CTA untuk merawat air sungai di Malaysia oleh proses osmosis hadapan boleh disiasat dan keadaan proses yang optimum akan ditentukan untuk mengatasi masalah kekurangan air di Malaysia.

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LIST OF ABBREVIATIONS

J_w	water flux
A	water permeability
n	Van't Hoff factor
M	Molarity
R	gas constant
T	absolute temperature
ΔP	hydrostatic pressure
J_s	reverse flux of the solute
B	solute permeability coefficient
ΔC	solute concentration difference across the membrane
C_F	bulk feed solution concentration
t_s	support layer thickness
t_A	active layer thickness
C_D^m	draw solute concentration in solution at the support layer side
C_F^m	draw solute concentration in solution at the boundary layer side
ΔV	volume of water which permeates through the membrane
A	effective area of the membrane
Δt	time taken for water permeation in minutes
R	humic acid rejection
C_p	humic acid concentration in permeate
C_b	bulk concentration of humic acid

Greek

$\Delta\pi$	Osmotic pressure difference across the membrane
π	Osmotic pressure
π_D	Bulk osmotic pressure of the draw solution
π_F	Bulk osmotic pressure of the feed solution
δ	external boundary layer of thickness

Subscripts

p	permeate
b	bulk
D	draw solution
F	feed solution

LIST OF ABBREVIATIONS

CP	Concentration polarization
CTA	Cellulose Tri Acetate
DS	Draw solution
ECP	External concentration polarization
FESEM	Field Emission Scanning Electron Microscopy
FO	Forward osmosis
FS	Feed solution
HA	Humic acid
HTI	Hydration Technology Inc.
ICP	Internal concentration polarization
MD	Membrane distillation
MF	Microfiltration
NF	Nanofiltration
NMWL	Nominal molecular weight limit
NOM	Natural organic matter
OMBR	Osmotic Membrane Bioreactor
RO	Reverse osmosis
TFC	Thin film composite
UF	Ultrafiltration

1 INTRODUCTION

1.1 Background

With the rapid increase in global population and the development of industries, the demands for freshwater have increased drastically whereas the available water sources have remained limited and are unevenly distributed. In highly industrialized countries, there are growing problems of providing adequate water supply and properly disposing of municipal and industrial used water. In developing countries, particularly those in arid parts of the world, there is a need to develop low-cost methods of acquiring new water supply while protecting existing water sources from pollution. In response to these issues in this century, intensive research on finding alternative solutions to supplement insufficient freshwater sources has been carried out, particularly in the field of desalination and water treatment.

In desalination and water reclamation processes, membrane technologies, such as reverse osmosis (RO), have increasingly being adopted to produce freshwater from alternative water resources due to water scarcity. Currently, RO is one of the most commonly used desalination technologies due to the availability of stable and good performance membranes, which are permeable to water but highly impermeable to salts, organic matters and other pollutants. Moreover, RO has a relatively lower overall cost compared to traditional thermal processes, which make use of excessive thermal energy while achieving a low feed-water recovery (Reddy & Ghaffour, 2007). In the RO process, a high applied pressure (1-10 MPa) is used to force water from a region of high solute concentration to permeate through an RO membrane to a region of low solute concentration, with the solute being retained (Ozaki, 2004). As a result, the requirement for the high applied pressure which leads to high energy consumption as well as the requirement for high strength equipments which can withstand the high applied pressure, leads to a high operational cost and makes RO significantly more expensive than conventional water treatment technologies (Fritzmman et al., 2007). Moreover, limited recovery, typically 35–50% for seawater (Liu et al., 2009), is another drawback of RO.

Forward osmosis (FO), a recently resurgent membrane process, is a membrane process that utilizes a draw solution that can generate high osmotic pressure as a driving force for

separation (Loo et al., 2012). It is developed as a possible alternative technology for desalination and water reclamation at a perceivably reduced cost. In FO, water flows from a low concentration feed water to high concentration draw solution under the concentration gradient across the semi-permeable membrane in FO membrane process. Unlike typical pressure-driven membrane processes where a hydraulic pressure is applied onto the feed water to “push” water through a membrane, forward osmosis occurs spontaneously without the need of externally applied pressure (Cath et al., 2006). FO is highly attractive due to its significantly lower energy demand for pumping. In recent years, FO has been considered as a potential alternative to pressure-driven membrane processes and has attracted much attention from various research groups. Its potential applications may include food processing, water and wastewater treatment, desalination, as well as electricity generation via a derivative pressure retarded osmosis process.

During the last four decades, several reports were published on the FO process. The main focuses were on achieving a better flux performance and on the use of different types of chemicals, such as sulfur dioxide (SO_2), aluminium sulphate ($\text{Al}_2(\text{SO}_4)_3$) or glucose, that was either easily removable or consumable as the draw solution (Batchelder, 1965; Frank, 1972; Kravath, 1975; Stache, 1989). Later on, a two-stage FO process was patented, with potassium nitrate (KNO_3) and sulfur dioxide (SO_2) being used as the draw solution in the first and second stage, respectively (McGinnis, 2002). In these attempts, the membrane used was of similar characteristics to the Loeb–Sourirajan type cellulose acetate membrane. In the study of McCutcheon et al. (2005), the performances of the two FO membranes were tested. The membranes are denoted by the manufacturer (GE Osmonics) as AG and CE and are used for brackish water RO. The AG membrane is a polyamide thin film composite membrane formed by interfacial polymerization on a polysulfone backing. The CE membrane is a cellulose acetate asymmetric membrane. However, it was found that severe internal concentration polarization still happened within the FO membranes, which suggested that this FO membrane was not ideal for the FO process. This lack of a suitable membrane, as well as the draw solution, was recognized to be the hindrance for the development of the FO process.

Although the novel concept of forward osmosis was developed as early as 1968 (Popper et al., 1968), it has not been able to advance mainly due to lack of suitable forward osmosis membranes and lack of suitable draw solution. According to the research done by Xu et al. (2010), a higher water flux can be achieved by increasing draw solution

concentration as increase in concentration will also increase the osmotic pressure thus promoting the process of forward osmosis. Therefore, it is important to determine how the FO system performs with respect to the membrane performance criteria (water flux and salt rejection) under a range of osmotic driving forces to advance the FO membrane process technology.

1.2 Motivation

Water is generally known as an important necessity for all activities such as living consumption, industries, agricultural washing and bathing. Clean drinking water is essential to human and other living things. For increasing population in Malaysia nowadays, drinking water is taken primarily from surface water sources like rivers, lakes, and reservoirs. However, the sources of the clean drinking water are contaminated by chemical constituents (organics, inorganics and gases) and physical contaminants (colour, odour and solid) (Srivastava, 2011). In rivers, about 50 % of the dissolved organic materials are humic substances that affect pH and alkalinity (Kile & Chiou, 1989). The principal constituent of humic substances is humic acid which is a natural organic matter (NOM) that causes the colour of fresh water to turn dark brown at high concentration. As a result, the river water in Malaysia needs to be treated correctly at low cost and energy before consuming by the citizens.

Among many water treatment methods, osmosis is the most common method used in desalination of water. For this research, forward osmosis was chosen over reverse osmosis as the process to treat river water due to the fact that the process of reverse osmosis has high cost, high energy consumption and has limited recovery which is roughly about 30%-50% (Chekli et al., 2012; Liu et al., 2009). On the other hand, the process of forward osmosis can be done at lower cost, energy and also has higher recovery rate (McGinnis & Elimelech, 2008). Although FO has a number of advantages, one of its challenges is the lack of optimized membrane to produce high water flux. The current only available commercial FO membranes are developed by HTI (Hydration Technologies Inc., OR) using cellulose triacetate (CTA) as the membrane material (Herron, 2008). It is suitable to be used to treat river water as it is not prone to biodegradation and hydrolysis compared to other fabricated membranes (Ong & Chung, 2012).

There are a lot of studies have been done related to desalination of seawater particularly by using RO techniques. However, researches based on river water treatment by using membrane processes are scarce especially by using FO membrane process. In order to produce high quality drinking water that is conforming to drinking water quality standard in Malaysia, the application of FO in river water treatment is needed to be examined. In addition, the performance of CTA membrane in NOM removal of river water using FO membrane process is worth studying. This technique is believed to be able to help the citizens who live in rural areas without clean water and far away from the city's water pipes.

1.3 Problem statement

The following are the problem statements of this research:

- 1) RO is the benchmark in membrane-based water treatment but its efficiency and sustainable operation are hampered by membrane fouling & high energy consumption.
- 2) FO can be a sustainable alternative membrane system for humic acid removal to minimize energy consumption and lower membrane fouling. However, one of the challenges of FO is the reverse salt diffusion which could affect its performance.
- 3) FO process is a recently resurgent membrane process, therefore it is lack of suitable membrane and draw solution to optimize the process.

1.4 Objective

The objective of this research is to characterize cellulose triacetate (CTA) forward osmosis membrane based on its performance in humic acid removal by using NaCl as draw solution with different concentrations and humic acid as feed solution with different pH.

1.5 Scope of research

To achieve the objective of the current work, three main scopes of research had been identified. First of all, the CTA membrane was characterized in terms of pure water permeability. This is done by determining the water flux of desired solution across the membrane from feed solution to the draw solution by using draw solution at different

concentrations and feed solution at different pH. The results will help in determining the optimal concentration of draw solution to be used in forward osmosis process for river water. In addition, CTA membrane was characterized in term of physical properties by using Field Emission Scanning Electron Microscopy (FESEM). The surface morphology and properties of the membrane were determined.

The second scope of this research is to study the ability of FO CTA membrane for humic acid removal. This is done by checking the absorption value of draw solution after the experiment by using UV-vis spectrophotometer to determine the presence of humic acid that will probably be found in the product draw solution. It can also determine how acceptable the product is to be consumed by human being.

Last but not least, to study the effect of different concentration draw solution (i.e. NaCl) on reverse salt diffusion. This is completed by determining the conductivity value of the feed solution before and after the experiment to check the existence of salt that will possibly backflow to the feed solution through the membrane. Different humic acid feed solution pH and NaCl draw solution concentrations were used to determine how it affects the amount of reverse salt diffusion.

1.6 Organisation of this thesis

The structure of the reminder of the thesis is outlined as follow:

Chapter 2 introduces the membrane technology used in water treatment and the fundamental principles of osmosis and forward osmosis (FO). Besides that, this chapter discusses on the advantages of using FO method and its applications. The differences between FO and the current most popular membrane process RO are also compared. In addition, this chapter provides a description on the different method of membrane technologies currently used in this era. Furthermore, this chapter discusses on the common membrane used for forward osmosis process known as cellulose triacetate (CTA) membrane and the discussion on the humic acid is also done as it is the feed solution for this research. The selection of NaCl draw solution and its properties that could influence the FO performance is also discussed on this chapter. Lastly, this chapter also looks into the current challenges of FO that can gravely affect the efficiency of the process which are concentration polarization, reverse salt diffusion of draw solution and draw solution recovery.

Chapter 3 provides description on the chemicals used and methodology of this research which includes the procedures to characterize CTA FO membrane in terms of physical and chemical properties. The preparation of draw solution and feed solution will be described and the permeation module of the experiment will be demonstrated.

Chapter 4 discusses on the experimental data which was obtained. This chapter discusses on the performance of different draw solution concentrations by means of water flux from feed to permeate side, humic acid rejection and also reverse salt diffusion. In addition, the impact of pH on CTA membrane performance at different draw solution concentrations is discussed too. Lastly, determination of the optimal draw solution concentration and feed solution pH in treating river water is completed.

Chapter 5 draws together a summary of the thesis and provides some recommendations to improve the research.

2 LITERATURE REVIEW

2.1 General overview

First of all, this chapter introduces the membrane technology used in water treatment and the fundamental principles of osmosis and forward osmosis (FO). This chapter also discusses on the advantages of using FO in water treatment over the current most popular membrane process which is the reverse osmosis (RO). The applications of FO are also will be discussed. Besides that, this chapter discusses and compares the other pressure-driven membrane processes, namely reverse osmosis (RO), nanofiltration (NF) ultrafiltration (UF), and microfiltration (MF). Apart from that, this chapter also reviews on the properties of cellulose triacetate (CTA) membrane which makes it a suitable membrane for forward osmosis membrane. A review on humic acid is also present in this chapter as it is the main feed solution which was used for this study. Moreover, the selection of sodium chloride (NaCl) draw solution will be discussed. This chapter also discusses the properties of draw solution that will affect FO performance which are concentration and temperature. Lastly, the current challenges of FO that can gravely affect the efficiency of the process which are concentration polarization, reverse salt diffusion of draw solution and draw solution recovery are also present in this chapter.

2.2 Introduction to membrane technology in water treatment

Under the threats of freshwater shortage, many engineers and researchers have been dealing with reclaiming polluted water, while others try to find other alternative sources. Nowadays, desalination for seawater and other water sources, as well as water reclamation, is becoming a more and more attractive method to produce high quality water for both industrial and domestic usage. With this rapid development, membrane technology has become economically attractive for water treatment. Membrane technology is the application of a positive barrier or film in the separation of unwanted particles, microorganisms and substances from water and effluents. Membrane technology is gaining popularity due to its ability to remove organic and inorganic substances, micropollutants and some harmful chemicals which cannot be removed by conventional water treatment system.

A membrane is a thin, typically planar structure or material that selectively controls the mass transport between two environments or phases. Organic polymers, metals, ceramics, layer of chemicals, liquids and gases can be membrane (Khulbe, 2008). In this separation process, a semi-permeable membrane acts as a highly specific filter that is capable of separating substances because of differences in their physical and chemical properties under a variety of driving forces. Examples of these driving forces are the application of high pressure, the introduction of electric potential and the maintenance of concentration gradient across a membrane (Strathmann, 2001). A schematic representation of membrane separation is given in Figure 2-1.

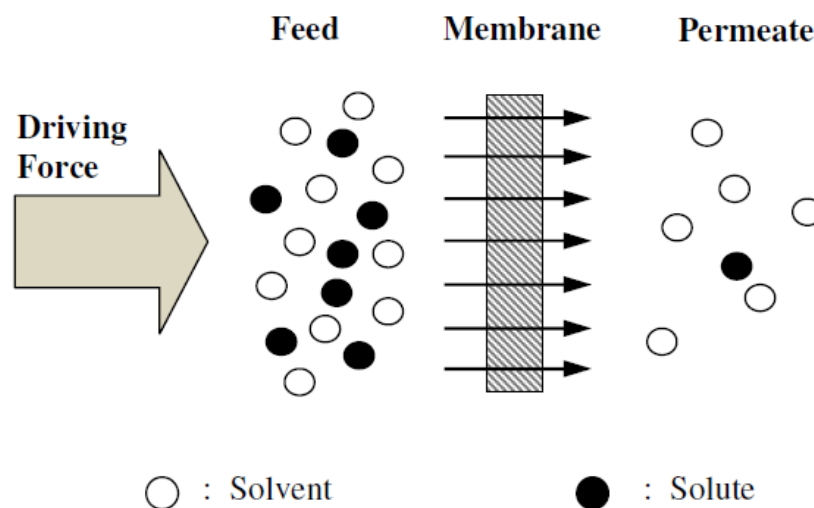


Figure 2-1: Schematic representation of a membrane process for separation (Khulbe, 2008).

2.3 Types of pressure-driven membrane processes

2.3.1 Reverse Osmosis

The current state-of-the-art for desalination and water purification is RO process, for it can remove salts, hardness, turbidity and most of potable water contaminants known today. Reverse osmosis is a pressure-driven membrane-based process, where the membrane (almost always polymers) acts as the heart of the process in separating the undesired constituents from a feed to obtain the desired pure product (Matin et al., 2011). Figure 2-4 shows the process model of reverse osmosis process (Chekli et al., 2012). Nowadays, the most popular membrane processes for saline water treatment are Reverse

Osmosis (RO), Microfiltration (MF), Ultrafiltration (UF) and Nanofiltration (NF). Membrane permeability and the size of constituents rejected by each process decrease in the order presented (MF > UF > NF > RO) (Coday et al., 2014). Table 2-2 shows the general description of these four membrane processes. RO process enjoys a number of advantages which make it an attractive technology for seawater desalination because of its reliability, high water recovery rate and salt rejection rate, and its ability to treat a wide range of seawater concentrations. At present, more than 50% of the world's desalination water is produced by RO process (Altaee et al., 2014).

Although RO process has a number of advantages, the high power consumption is the process's main disadvantage. With the Energy Recovery Instrument (ERI), an average of 3.5 kWh/m³ is required for seawater desalination (seawater TDS 35,000 mg/L). Indeed, reducing power consumption in the process of reverse osmosis was the objective of many research studies (Altaee et al., 2014). Other than that, RO is highly susceptible to inorganic scaling and to particulate, biological, and organic fouling. These foulants can become compacted and difficult to clean, leading to low water permeability, increased pressure loss, and considerable chemical consumption for cleaning (Coday et al., 2014). In addition, designing an efficient RO desalination system involves many complicated and interacting choices to meet the technical, environmental and economic requirements. One of the main problems in reverse osmosis plants is concentration polarization. Prediction of solute concentration on the membrane surface in crossflow membrane processes has vital role in the design of reverse osmosis processes and in estimating their performances (Sassi & Mujtaba, 2011). All these problems can compromise membrane performance and surface chemistry.

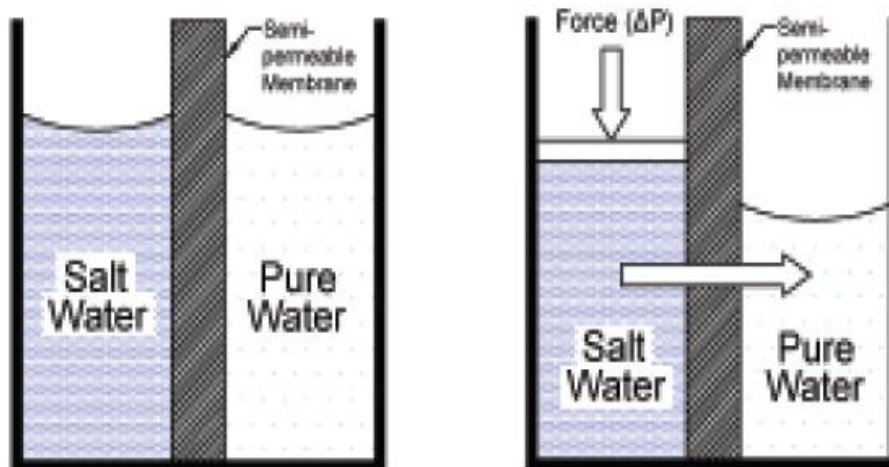


Figure 2-2: Process model of reverse osmosis (Duranceau, 2012).

2.3.2 Nanofiltration

NF membranes have a nominal pore size of approximately 2-5nm (Ozaki, 2004). Pushing water through these smaller membrane pores requires a higher operating pressure than either MF or UF. Operating pressures are usually near 600 kPa (90 psi) and can be as high as 1,000 kPa (150 psi) (Rautenbach et al., 1996). These systems can remove virtually all the cysts, bacteria, viruses, and humic materials. They provide excellent protection from disinfection byproducts formation if the disinfectant residual is added after the membrane filtration step. Because NF membranes also remove alkalinity, the product water can be corrosive, and measures, such as blending raw water and product water or adding alkalinity, may be needed to reduce corrosivity (Greenlee et al., 2009). NF also removes hardness from water, which accounts for NF membranes sometimes being called “softening membranes”. Hard water treated by NF will need pretreatment to avoid precipitation of hardness ions on the membrane (Rautenbach et al., 1996). More energy is required for NF than MF or UF, which has hindered its advancement as a treatment alternative.

2.3.3 Ultrafiltration

Ultrafiltration (UF) is the process of separating extremely small particles and dissolved molecules from fluids. The primary basis for separation is molecular size, although in all filtration applications, the permeability of a filter medium can be affected by the chemical, molecular or electrostatic properties of the sample (Basile & Nunes, 2011). Ultrafiltration can only separate molecules which differ by at least an order of magnitude in size. Molecules of similar size cannot be separated by ultrafiltration. Materials ranging in size from 1,000 to 1,000,000 molecular weight are retained by ultrafiltration membranes, while salts and water will pass through (Khaled, 2013). Colloidal and particulate matter can also be retained. Ultrafiltration membranes can be used both to purify material passing through the filter and also to collect material retained by the filter. Materials significantly smaller than the pore size rating pass through the filter and can be depyrogenated, clarified and separated from high molecular weight contaminants. Materials larger than the pore size rating are retained by the filter and can be concentrated or separated from low molecular weight contaminants (Schwab & Moore, 2012).

Ultrafiltration is typically used to separate proteins from buffer components for buffer exchange, desalting, or concentration. Ultrafiltration are also ideal for removal or exchange of sugars, non-aqueous solvents, the separation of free from protein-bound ligands, the removal of materials of low molecular weight, or the rapid change of ionic and/or pH environment. Depending on the protein to be retained, the most frequently used membranes have a nominal molecular weight limit (NMWL) of 3 kDa to 100 kDa (Khaled, 2013). Ultrafiltration is far gentler to solutes than processes such as precipitation. UF is more efficient because it can simultaneously concentrate and desalt solutes. It does not require a phase change, which often denatures labile species, and UF can be performed either at room temperature or in a cold room (Basile & Nunes, 2011).

2.3.4 Microfiltration

Microfiltration (MF) is the process of removing particles or biological entities in the 1.5 μm to 10.0 μm range from fluids by passage through a microporous medium such as a membrane filter. Although micron-sized particles can be removed by use of non-membrane or depth materials such as those found in fibrous media, only a MF membrane having a precisely defined pore size can ensure quantitative retention (Ozaki, 2004). MF membrane can be used for final filtration or pre-filtration, whereas a depth filter is generally used in clarifying applications where quantitative retention is not required or as a pre-filter to prolong the life of a downstream membrane. MF membrane and depth filters offer certain advantages and limitations. They can complement each other when used together in a microfiltration process system or fabricated device (Basile & Nunes, 2011). The retention boundary defined by a MF membrane can also be used as an analytical tool to validate the integrity and efficiency of a system. For example, in addition to clarifying or sterilizing filtration, fluids containing bacteria can be filtered to trap the microorganisms on the membrane surface for subsequent culture and analysis. Microfiltration can also be used in sample preparation to remove intact cells and some cell debris from the lysate (Rautenbach et al., 1996). Membrane pore size cut-offs used for these types of separation are typically in the range of 10 to 1000 nm.

Table 2-1: General descriptions of RO, NF, UF and MF membrane processes (Ozaki, 2004).

Particulars	Reverse Osmosis (RO)	Nanofiltration (NF)	Ultrafiltration (UF)	Microfiltration (MF)
Pore size (nm)	No-detectable pore size	2 - 5	3 - 10	10 – 1000
Retain Particulars (MW)	< 350	> 150	1,000 - 300,000	> 300,000
Applied Pressure (MPa)	1 – 10	0.3 – 1.5	0.01-0.3	0.005 – 0.2
Material	1. Aromatic polyamide 2. Cellulose acetate	1. Aromatic polyamide 2. Polyvinyl alcohol	1. Polysulfone 2. Polyimide 3. Polyacrylonitrile Ceramics	1. Polyethylene 2. Polypropylene 3. Polyvinylidene fluoride 4. Ceramics
Main Function	1. Desalination of brackish and seawater. 2. Production of ultra-pure water.	1. Removal of micropollutants. 2. Desalination of brackish water. 3. Concentration on chemicals.	1. Drinking water production. 2. Clarification of fruit juice. 3. Membrane bioreactor. 4. Home water purifiers.	1. Removal of fine particles and bacteria. 2. Pre-treatment for RO and UF. 3. Membrane bioreactor.

Besides pressure-driven membrane processes, there is another type of membrane process which is forward osmosis (FO) that operates by utilizing the osmotic pressure caused by concentration gradient. This will be discussed in the next topic.

2.4 Forward osmosis

2.4.1 Osmosis and osmotic pressure

According to Helfer et al. (2014), osmosis occurs when two solutions of different concentrations (for example, different salinities) are separated by a membrane which will selectively allow some substances through it but not others. If these two solutions are fresh water and seawater, for example, and they are kept separated by a semipermeable membrane that is only permeable to water, then water from the less concentrated solution side (freshwater) will flow to the more concentrated solution side (seawater). According to McCutcheon et al. (2005) theoretically, the water flux in an osmosis process can be described as shown in equation (2.1) below:

$$J_w = A \Delta\pi \quad (2.1)$$

where J_w is the water flux, A is the pure water permeability coefficient while $\Delta\pi$ is the difference in osmotic pressures across the membrane between the draw and feed solution sides. This flow will continue until the concentrations on both sides of the membrane are equalized or the pressure on the concentrated solution side is high enough to stop further flow. Under no flow conditions, this pressure will be equal to the osmotic pressure of the solution. Osmotic pressure is a pressure applied to the solution (but not the solvent) from outside in order to just prevent osmotic flow. Osmotic pressure is a colligative property which indicates the chemical potential of the solvent in the solution, or alternatively it includes vapour pressure lowering, boiling point elevation, freezing point depression and osmotic pressure (Rudin, 1999). The osmotic pressure (π) of an ideal dilute solution is given by Van't Hoff's equation as shown as equation (2.2) below:

$$\pi = nMRT \quad (2.2)$$

Where n is the Van't Hoff factor (accounts for the number of individual particles of compounds dissolved in the solution, for example $n=2$ for NaCl, $n=1$ for glucose), M is the molar concentration (molarity) of the solution, R is the gas constant ($R=0.0821$ L atm mol⁻¹ K⁻¹) and T is the absolute temperature (K) of the solution.

2.4.2 Fundamental principle of forward osmosis

Forward osmosis (FO) (also known as manipulated osmosis or engineered osmosis) is one of the emerging membrane technologies as it has the ability to desalinate seawater or brackish water at low-cost energy compared to traditional processes. The novelty of this process lies in utilizing the natural osmotic process for desalination rather than the hydraulic pressure as in Reverse Osmosis (RO). Figure 2-2 explains the fundamental of forward osmosis process. Forward osmosis is the transport of water through a semipermeable membrane from a relatively low concentration solution (feed) to a relatively high concentration solution (draw), that is, from a high to low water chemical potential (Wong et al., 2012). A synthetic membrane separates a feed stream and a concentrated draw solution, and the osmotic pressure difference ($\Delta \pi$) across the membrane facilitates diffusion of water through the membrane while rejecting almost all dissolved and suspended constituents. Commonly, the FO process is completed in two separate steps: 1) recovery of water from a feed stream and dilution of the draw solution, and 2) production of high quality product water using RO or distillation while reconcentrating the draw solution. The reconcentrated draw solution is then reused in the FO process (Coday et al., 2014).

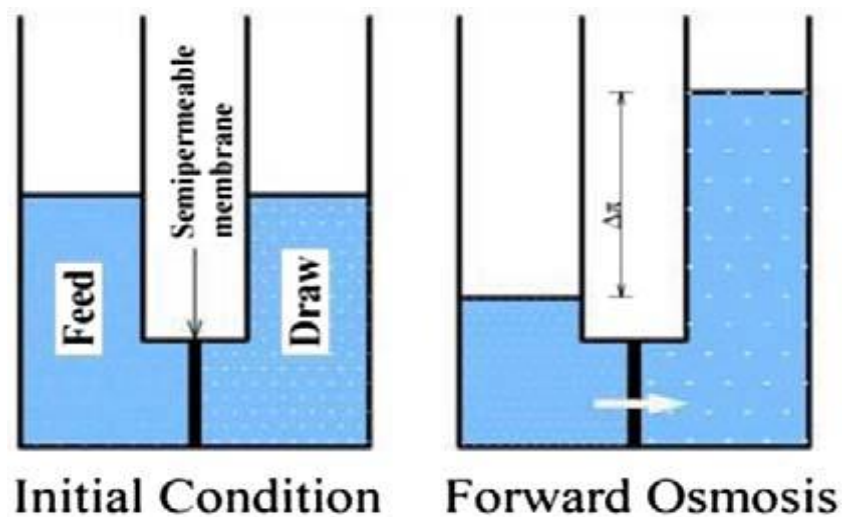


Figure 2-3: The principle of forward osmosis (FO) (Chekli et al., 2012).

2.4.3 Advantages of forward osmosis

FO has many advantages over other membrane technologies. High rejection of almost all solutes and suspended solids while operating at very low or no hydraulic pressures and ambient temperature is the greatest benefits of FO (Coday et al., 2014). Besides, the advantages of using FO are that it can achieve high rejection of a wide range of contaminants, and it may have lower irreversible fouling than pressure-driven membrane processes such as the current most popular membrane process, Reverse Osmosis (RO) because of the lack of applied hydraulic pressure. Table 2-1 is the comparisons of RO with FO. It shows that FO has many advantages over RO in terms of driven pressure, water recovery, environment effect, membrane fouling, modules, application, energy consumption and equipments. These advantages significantly reduce energy consumption and capital costs associated with pumping and system design and construction. They also allow for the development of highly modular systems that can be operated in harsh conditions with minimal access to electric power and supplies (Mi & Elimelech, 2010).

According to Achilli et al. (2009), recent studies have demonstrated that membrane fouling in forward osmosis is relatively low and this is supported by which state that the absent of hydraulic pressure in forward osmosis which depends on osmotic gradient reduces the chance of foul material to remain on the surface of membrane, more reversible and can be minimized by optimizing the hydrodynamics (Lee et al., 2010). Forward osmosis also has the potential to help achieve high water flux and high water recovery due to the high osmotic pressure gradient across the membrane. High water recoveries could help reduce the volume of desalination brine, which is a major environmental concern forward for current desalination plants, particularly for inland desalination (McCutcheon et al., 2005).